

A seven square degrees survey for galaxy-scale gravitational lenses with the HST imaging archive [★]

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Abstract

We present the results of a visual search for galaxy-scale gravitational lenses in $\sim 7^{\circ 2}$ of Hubble Space Telescope (HST) images. The dataset comprises the whole imaging data ever taken with the Advanced Camera for Surveys (ACS) in the filter F814W (I-band) up to August 31st, 2011, i.e. $6.03^{\circ 2}$ excluding the field of the *Cosmic Evolution Survey* (COSMOS). In addition, we have searched for lenses in the whole Wide Field Camera 3 (WFC3) near-IR imaging dataset in all filters ($1.01^{\circ 2}$) up to the same date. Our primary goal is to provide a sample of lenses with a broad range of different morphologies and lens-source brightness contrast in order to design and train future automated lens finders in view of all-sky surveys. Our criteria to select lenses are purely morphological as we do not use any color or redshift information. The final candidate selection is very conservative hence leading to a nearly pure but incomplete sample. We find 49 new lens candidates: 40 in the ACS images and 9 in the WFC3 images. Out of these, 16 candidates are secure lenses owe to their highly recognizable morphology, 21 more are very good candidates, and 12 more have morphologies compatible with gravitational lensing. The imaging dataset is heterogeneous in depth and spans a broad range of galactic latitudes. It is therefore insensitive to cosmic variance and allows to estimate the number of galaxy-scale strong lenses on the sky for a putative survey depth. Because of the incompleteness of the sample, the estimated lensing rates should be taken as lower limits. Using these, we anticipate that a $15\,000^{\circ 2}$ space survey such as Euclid will find at least 60 000 galaxy-scale strong lenses down to a limiting AB magnitude of $I=24.5$ ($10\text{-}\sigma$) or $I=25.8$ ($3\text{-}\sigma$).

Key words. Gravitational lensing: strong, Galaxies: statistics, catalogs, surveys.

1. Introduction

Gravitational lensing in its weak and strong regimes is currently one of the best tools to study dark matter and dark energy (e.g. Hu 1999). It is also the most reliable way to weight precisely galaxies up to several effective radius (e.g. Gavazzi et al. 2007). In combination with stellar dynamics, it provides the complementary measurement to determine the lens mass profile (e.g. Barnabè et al. 2009) and to break the disc-halo degeneracy in spiral galaxies (e.g. Dutton et al. 2011). Thanks to large sample of strong lenses, statistical studies of galaxy mass properties and evolution with redshift are feasible (e.g. Faure et al. 2011, 2009; Lagattuta et al. 2010; Auger et al. 2010; Koopmans et al. 2006). In some cases, when the radial extent of an Einstein ring is particularly large or when sources at multiple redshifts are lensed by the same object (e.g. Gavazzi et al. 2008), the measurement of the mass slope in the lens can be of exquisite quality and allow to constrain the cosmological parameters (e.g. Suyu et al. 2010) in a way fully competitive with other cosmological probes (see Suyu et al. 2012, for a short comparison of the methods).

Even with a few hundreds of strong lenses in hand, current samples remain small and must be drastically extended to allow one for high precision statistical studies and to provide a genuine understanding of the distribution of visible and dark matter in galaxies. The increasing number of optical all-sky surveys either from the ground or from space, lends considerable hope to build such large samples, with tens or even hundreds of thousands of

objects. However, the automated techniques available to find the lenses from petabytes of imaging data are so far limited in their efficiency and tend to produce a large number of false positives that require significant post-processing cleaning.

Among the best automated robots to find lenses are "Arcfinder" (Seidel & Bartelmann 2007), which was primarily developed to find large arcs behind clusters and groups, and the algorithm by Alard (2006) used by Cabanac et al. (2007) and More et al. (2012) which was optimized to look for arcs produced by individual galaxies and groups in the CFHT Strong Lensing Legacy Survey (SL2S). While the latter techniques do not rely on any model for the mass distribution in lens galaxies, other automated robots consider any galaxy as a potential lens and predict where lensed images of a background source should be before trying to identify them on the real data (Marshall et al. 2009).

These robots are being built and trained to mimic the performances of the human eye/brain in recognizing a lens system among other astronomical objects. To perform this training efficiently, we need to build strong lens samples with large varieties of image configurations. So far, the most efficient way in this respect is the visual inspection of a significant portion of the sky, with the goal of providing a test bench to devise, test and calibrate automated robots. Such robots will be mandatory to carry out lens searches in surveys of intractable size for a few astronomer, i.e., the all-sky surveys that may take place in the next decade. An alternative to robots will be the search for strong lenses by citizens in projects like the Galaxy Zoo (Lintott et al. 2008) and the future Lens Zoo (PI: P. Marshall). But we forecast that their contribution will be complementary to that of robots, in the action of classifying the robots numerous outputs.

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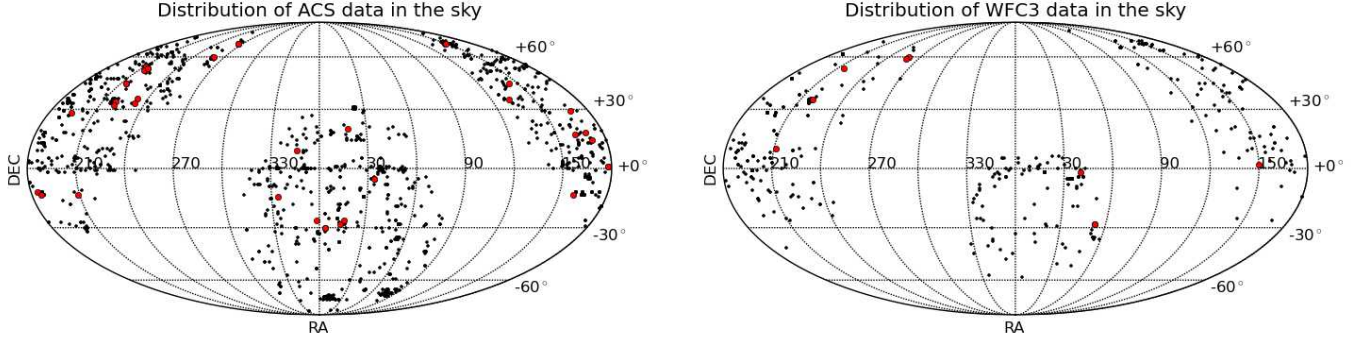


Figure 1. Distribution of the ACS (left) and WFC3 (right) images on the sky. The red dots indicate the position of the fields with a lens candidate. On the left panel, each point corresponds to a single ACS field of $11''^2$. The total area covered by the ACS is $6.03''^2$. On the right panel, each point corresponds to a single WFC3 field of $4.65''^2$. The total area covered by the WFC3 survey is $1.01''^2$.

Visual inspections of HST archive images in search for strong lenses have been successfully attempted in the past: Ratnatunga et al. (1999) found 10 lenses in the HST medium deep survey, followed by Moustakas et al. (2007) who found another few systems. So far, the largest search for strong lenses in HST images is the one conducted in the $1.64''^2$ field of view of the *Cosmic Evolution Survey* (COSMOS) (Scoville et al. 2007) by Faure et al. (2008) and Jackson (2008). They found in total 179 lens candidates among which 22 display multiple images of the source and/or have both lens and source redshifts to confirm their lens nature (see Faure et al. 2011).

In the present paper, we describe a search for strong lenses by visual inspection in all the HST images ever taken with the Wide Field Channel (WFC) of the Advanced Camera for Surveys (ACS) through the F814W filter (I-band). The total field of view explored is $6.03''^2$ and *excludes* the COSMOS field.

Since future wide field surveys will include near-IR imaging, we also carry out the experiment using the data taken with the Wide Field Camera 3 (WFC3) in the near-IR channel and the F160W filter. As the WFC3 is a rather new instrument on the HST and since the field of view of the camera itself is limited, the total area we cover in the near-IR is smaller than with the ACS data, i.e., $1.01''^2$.

Our goal with this work is both to provide a training set of lenses spanning a broad diversity in image configuration, hence helping to design automated searches and to estimate empirically the number counts of strong lenses as a function of depth. Throughout the paper, all magnitudes are in the AB magnitude system.

2. Dataset and characteristics

This work is all based on archival HST images from the Mikulski Archive for Space Telescopes (MAST) and its associated querying tool: the Hubble Data Archive (HDA)¹.

We searched for strong lenses in all the ACS imaging taken in the broadband I filter (F814W) and available in the archive on August 31st, 2011. We limited our search to the range of galactic latitude where the Milky Way does not lead to severe contamination by foreground objects and where the Galactic absorption is minimized, i.e., $l = [+30^\circ; +90^\circ]$ and $l = [-90^\circ; -30^\circ]$. The final calibrated, geometrically-corrected, dither-combined images

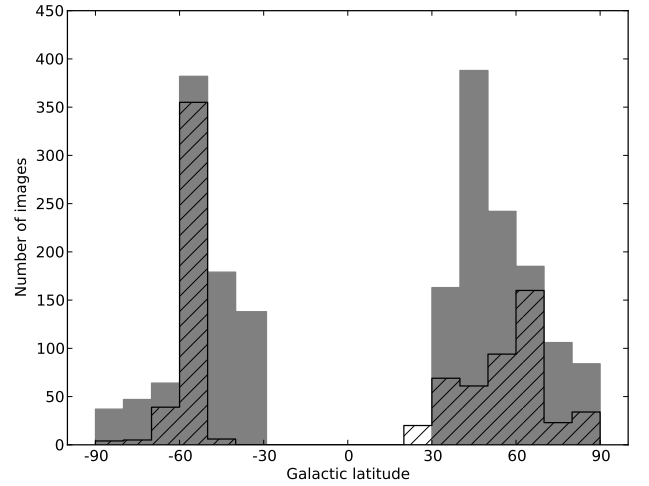


Figure 2. Distribution of the ACS (filled histogram) and WFC3 frames (dashed histogram) in galactic latitude.

with a pixel scale $0.05''/\text{pixel}$ were used for inspection. They cover a total of $6.03''^2$ of the sky.

We also carried out a near-IR search, using all the WFC3 image available in the archive on August 31st, 2011. Data were available in ten different filters (see Table 1) with Galactic latitudes in the range $l = [+20^\circ; +90^\circ]$ and $l = [-90^\circ; -50^\circ]$. The boundaries in galactic latitude are not only driven by our choice of avoiding the Milky Way, but also owe to the limited sample of images available for WFC3 which had its first light in June 2009. The final calibrated, geometrically-corrected, dither-combined images with pixel scale $0.13''/\text{pixel}$ were inspected. They cover a total of $1.01''^2$ of the sky.

In Fig. 1 we show the distribution of the ACS and WFC3 images on the sky and in Fig 2 we display the distribution of frames in galactic latitude. The combined ACS and WFC3 "surveys" totalize almost $7''^2$ of imaging data all over the sky.

For each ACS image, we estimated the depth using the ACS Exposure Time Calculator for imaging (ETC²), which is reliable for a very stable observatory such as the HST. This is also much

¹ <http://archive.stsci.edu/hst/search.php>

² <http://etc.stsci.edu/etc/input/acs/imaging/>

Table 1. The WFC3 dataset. Number of frames inspected per filter, and number of lens candidates found in every filter.

Filter	nb. frames	nb. lens
G141	38	0
F140W	39	2
F105W	61	1
F098M	55	0
F110W	80	1
F164N	13	0
F139M	74	0
F153M	2	0
F160W	396	3
F125W	112	2

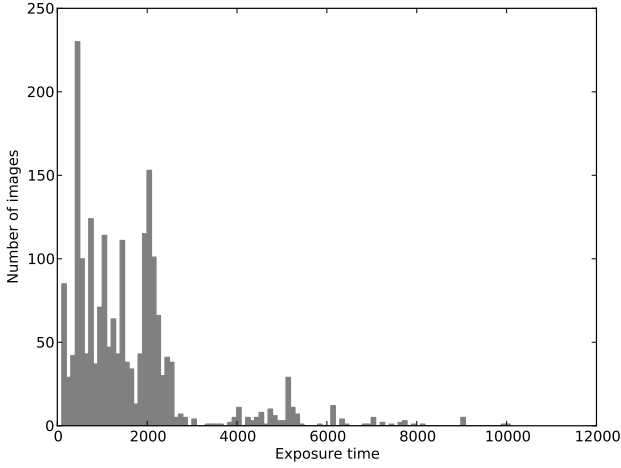


Figure 3. Distribution of the ACS/F814W images exposure time.

less demanding in terms of computing time than carrying out a full object detection on the actual data. Our detection limit corresponds to a total signal-to-noise ratio of 3 within an aperture of $1''^2$ ($3\text{-}\sigma$ detection).

In Section 4 we compare the results to that of COSMOS. This requires to measure the depth of our survey and that of COSMOS in the same way. Using the ACS ETC exactly in the same way for COSMOS and for our ACS F814W data we find a depth of $I=26.4$ mag for COSMOS, corresponding to an exposure time of 2028 s per pointing. Our estimate based on the ETC is well compatible with the limiting magnitudes quoted for COSMOS in other studies (Capak et al. 2007; Leauthaud et al. 2007).

The ACS frames of our archival survey span a very broad range of exposure times, as shown in Fig. 3. This translates into the distributions in depths displayed in Fig. 4, which peak in the bin $[26.0\text{--}26.5]$ mag, i.e., about the COSMOS depth (but the COSMOS data are not included in our search). For comparison in Fig. 4, the area covered by the COSMOS field would be $1.64^{\circ 2}$ for every depth up to $I=26.4$ mag.

3. The lens catalogue

3.1. The search by visual inspection

The HST images were inspected by two of the authors: RSP for the ACS images and RK for the WFC3 images, using a web browser and a Python interface designed to ease the image dis-

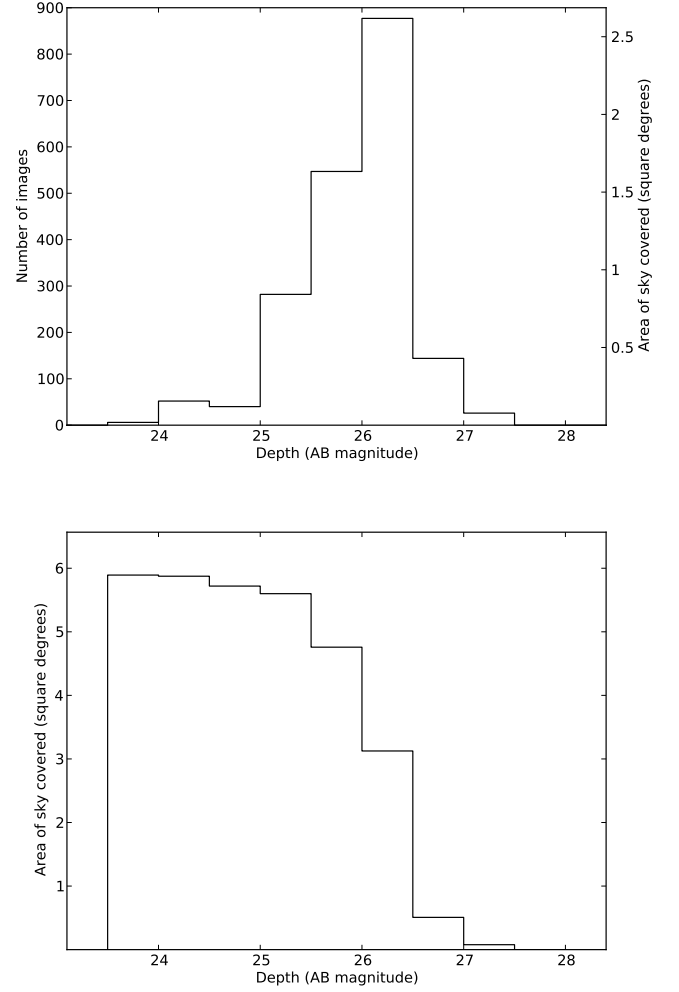


Figure 4. *Top panel:* The relative distribution of ACS image depths. The corresponding area of sky covered by the images of a given depth is shown on the right axis. *Bottom panel:* The cumulative area of the present survey as a function of depth.

play with custom intensity levels and scales adopted to each individual image, hence allowing us to explore the full dynamic range of the HST images. This is particularly useful to detect rings and arcs in the inner parts of galaxies and groups of galaxies, even without subtraction of the foreground light. This tool allows us to zoom into region of 500×500 pixels and generates jpeg and fits cut-outs images of the candidates. The coordinates of any candidate are obtained by interfacing with the Aladin Sky Atlas³. This simple tool allows us to inspect seven to ten HST frames per hour.

Some lens candidates were found right in the middle of the exposures, hence suggesting they were the primary targets for the observations. We identify those as being parts of already existing major lens catalogs including BELLS (Brownstein et al. 2012), CASTLES⁴, SL2S (Cabanac et al. 2007), SLACS (Bolton et al. 2006, 2008) and SWELLS (Treu et al. 2011). Obviously, we did not include these lenses in our catalogue, as they are not the result of a blind search.

³ <http://aladin.u-strasbg.fr/>

⁴ <http://www.cfa.harvard.edu/castles/>

A total of 40 new lens candidates were found in the ACS images (Figs. 5, 6 and 7) and nine more in the WFC3 images (Fig. 8). Color image composites were built for 16 lenses that had observations in at least two filters (Fig 9), helping to discriminate better between the foreground lens and the source. The filters used to built those color images are shown in Table 4. We stress that we do not use the color information as a mean to select the candidates.

3.2. Lens galaxy surface brightness

For all our lens candidates, we model and subtract the 2-D light distribution of the lensing galaxy(ies), both to detect any possible counter images for the detected arcs and to measure the magnitude of the lens.

To do so, we used GALFIT v3.0 (Peng et al. 2010) and fit a De Vaucouleur function. The code optimizes a number of parameters describing the lens galaxy: the galaxy total flux, effective radius (i.e., the half-light radius), axes ratio and position angle. Prior to the fit, a point spread function (PSF) was built using at least three stars in the vicinity of the lens and using the publicly available PSFEx software (Bertin 2011). In order to avoid contamination, the light from the arc(s) and close-by objects was masked out prior to the fit. Images of the best fit model and of the residuals after subtraction to the original image are displayed in Fig. 5 to 8. The parameters of the best fit light profiles are given in Tables 2 and 3. When more than a single galaxy is thought to be part of the lens potential several lines are given in the tables.

3.3. Lens type and classification

Our lens candidates are classified in different morphological types and a "reliability" criterion is also allocated to each system. This is summarized in the form of a 3-digit code in the "Comment" column of Tables 2 and 3:

- the first capital letter describes the shape of the source, i.e., whether it is an arc (A), a ring (R) or a point source (P).
- the second character gives number of lensed images seen either in the original image or in the image where the light profile of the lens has been subtracted image.
- the third, small case letter, is the confidence level for a candidate to be a genuine lensed system: #a indicates a "very high confidence" level that this system is an actual lens", #b "intermediate confidence that this system is an actual lens", and #c reflects the lower confidence level. The confidence level is based on morphological information such as the source size, its curvature, its distance in arc-second to the lens candidate.

We find, based solely on morphological criteria that 16 systems are surely genuine lenses and fall in the #a category. In addition, 21 systems are excellent candidates but from the present dataset their nature is less striking. For those, additional spectroscopy and color images would help ascertain the lensed nature. They are therefore categorized as #b. Finally, 12 systems fall in the #c category. They have an intriguing morphology which, to our opinion, could owe to gravitational lensing but may as well be chain galaxies, mergers, pairs with tidal tails, or ring galaxies. The lens nature of those systems must be confirmed with spectroscopy and lens modeling before being fully trusted. However, if confirmed, they would surely broaden the variety of known lens morphologies, as is needed to train correctly automated lens finders. For this reason, we keep these systems in our catalogue.

4. Comparison with other samples

The new lens search presented in this paper is fully based on the morphology of the candidates in a single band. There is no pre-selection of the best lens candidates in terms of stellar mass or size and we do not use any redshift information. Although direct comparisons with other lens searches are not straightforward, the work by Faure et al. (2008) in the COSMOS field shares many of our search characteristics, such as the visual inspection of ACS images.

Indeed the first lens sample in COSMOS was build by visually inspecting stamps images of pre-selected bright early-type galaxies. This affects the relative "success rate" of the two surveys, with COSMOS being biased towards more massive lenses by construction. We can nevertheless compare the main morphological characteristics of the two samples of lenses. In Fig. 10 we compare the first COSMOS lens sample and the present sample arc radius distributions, i.e., the distance between the arc center of light and the center of the lens galaxy. In Fig. 10 we also displays the lens effective radius distributions, using the best fits in Tables 2 and 3. When a lens candidate is made of two galaxies, the effective radius of the largest of the two is considered and the center of the lens is the light barycenter of the two galaxies. This concerns only 2 out of the 40 systems, and therefore cannot strongly influence the results. Together the radius distributions give an information on the mass distribution of the lens galaxy candidates and on the lenses and sources redshift distributions.

It is immediately seen that while the average effective radius of the lens galaxies in our sample is similar to that of COSMOS, the average arc radius is smaller in the present sample. This suggests that for a given effective radius, the lens galaxies in the present sample are less massive than in COSMOS. This is not surprising given the pre-selection of lens candidates done in COSMOS as explained above. However, this may also reflect a difference between the distance $D = D_s/(D_l D_i)$ between the lenses and the sources of the two samples, owing to the fixed depth in COSMOS on one hand, and to the inhomogeneous depth of the present dataset on the other hand. Still, while the details of the radius distributions are different, the overall shape remain similar in the two samples, that can be seen as a way to empirically estimate the number density of lens candidates on the plane of the sky in view of future large survey.

From the COSMOS field, Faure et al. (2008, 2011) find a density of ~ 10 to 20 lenses per square degree down to a depth $I=26.4$ mag depending on the degree of purity chosen. We find ~ 7 lenses per square degree in the present sample. The difference between COSMOS and the present counts may owe to cosmic variance, as a result for targeting a single line-of-sight in the case of COSMOS, and on the contrary, thousands of random line-of-sights in the present case (see Fig. 1).

In the case of the COSMOS field, the authors were benefiting from ground based imaging follow-up in multiple bands allowing them to use the color information to confirm the lens nature of their morphologically selected candidates. In the present case, in absence of color images we select the best candidates based only on their morphology. To avoid too many false positive, we have naturally selected secure lens candidates, such as partial rings, as #20, #27, #38 in Table 2, and arcs, as most of our lens candidates, rather than points sources. Indeed, arcs and rings are likely to be produced by lensing. On the contrary, multiple point sources can be found in many astrophysical objects. It is therefore more difficult to certify they are multiple images of a same source, particularly in absence of color images. When multiple point like image candidates are selected, like object #33

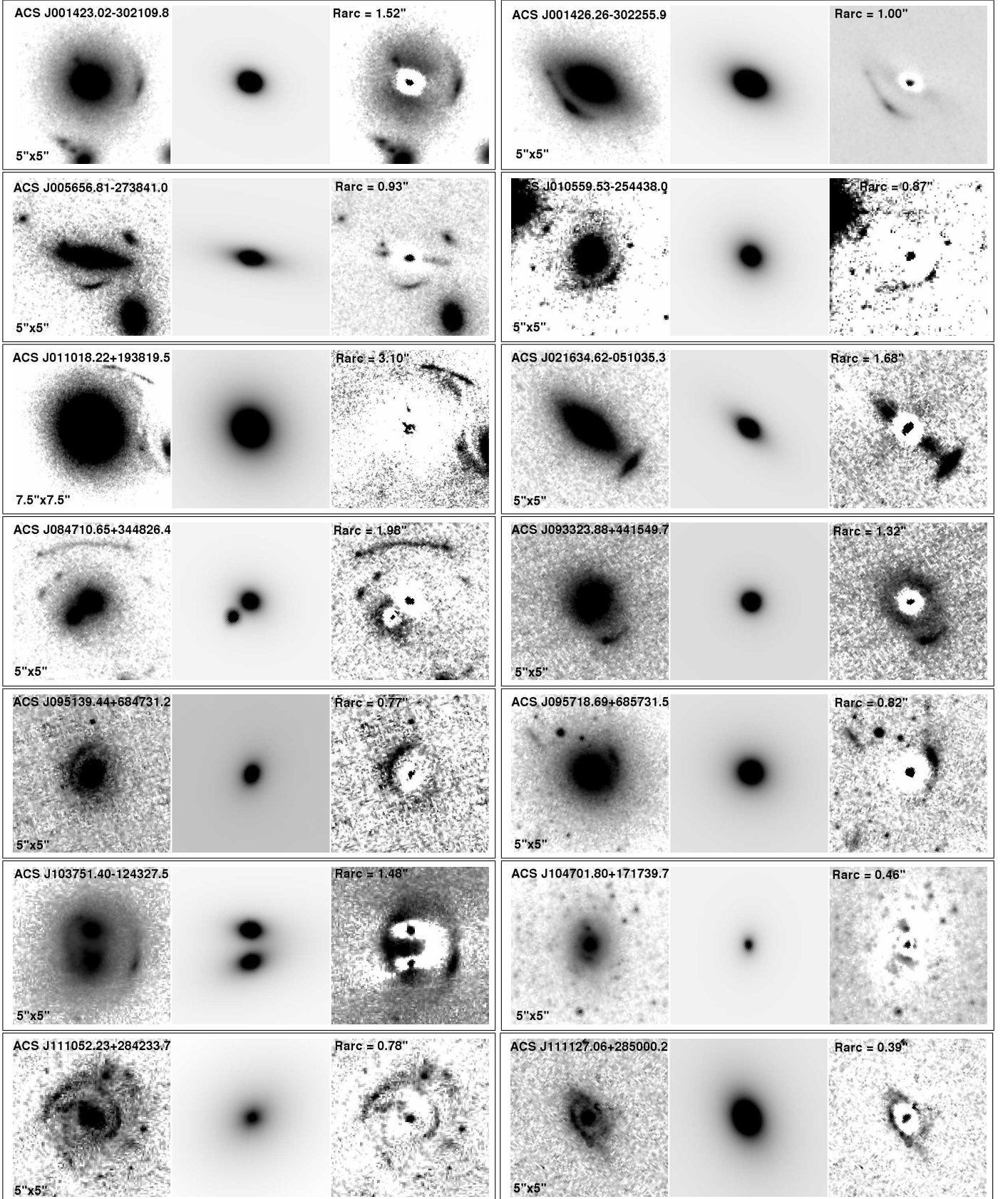


Figure 5. Lens candidates found by visual inspection of the ACS images. There are two lens candidates per line. For both are displayed in three panels : the ACS image, the 2-D light profile for the lens galaxy using GALFIT, and the image where the model is subtracted from the original data. Orientation of the images is north is to the top and East is to the left.

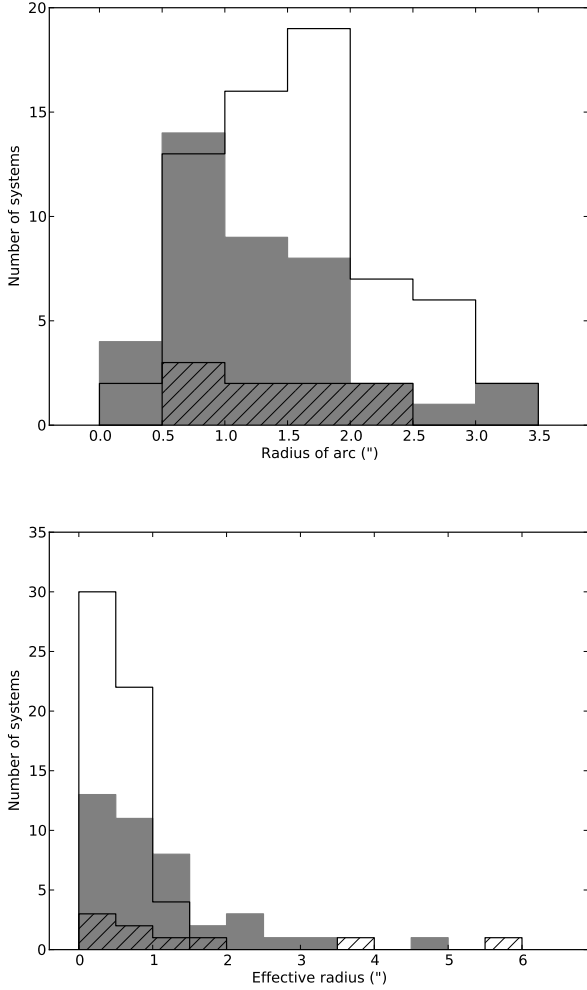


Figure 10. *Top:* the arc radii of the ACS lens candidates (filled), WFC3 candidates (hatched) and for the lenses from Faure et al. (2008) for the COSMOS survey (unfilled). *Bottom:* comparison of the effective radii of ACS lens candidates (filled), WFC3 candidates (hatched) and of the COSMOS survey (unfilled). For the present sample, when lens candidate is made of two galaxies effective radius of larger lensing galaxy is plotted.

in Table 2, one tends to favor quadruple systems over doubles, hence leading to an additional bias towards system where the lens and source are well aligned. This may also lead to select lenses displaying larger ellipticities than the general population of galaxies. Note, however, that some of our lenses would have been missed by the first COSMOS search, such as the low surface brightness lens #33 or the arc produced by a merger like object #27.

Finally the difference between our new lens count and the one of COSMOS may well reflect the amount of time spent per unit area inspected. At the depth of COSMOS our survey is already twice larger than the COSMOS field (Fig. 4) and our manpower is limited to a single astronomer for the ACS $6.03^{\circ 2}$ dataset, and another one for the WFC3 $1.01^{\circ 2}$ dataset. The search for lenses in the first COSMOS sample was made by four people. Still, the lens counts are comparable, suggesting that our estimations are close to true lens counts that a purely morphological search would find, and are at least a good lower limit.

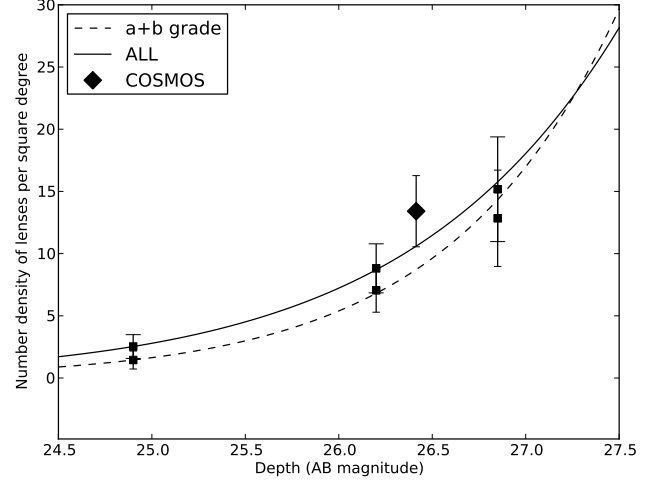


Figure 11. Number density of strong lenses in the HST ACS/F814W archival survey. A total of forty lenses are shown as a function of the survey depth, i.e. each point shows the number of lenses found in a survey of the depth displayed on the *x-axis*. We plot two curves depending on the confidence level allocated to the lens candidates (see text). For comparison, the diamond-shape point corresponds to the 22 most secure lenses in COSMOS.

5. Prospects for future space based all-sky surveys

The specificity of our survey consists in its high spatial resolution, its large field of view, and its variable depth. This allows us to give the lensing rate as a function of depth, as summarized in Fig. 11. In this Figure, we give the number density of strong lenses for a survey with a limiting depth as given on the *x-axis*. To keep a reasonable number of lenses per magnitude bin, we split our sample in three and we fit a power-law, $N = A m^a$, to the data. The result of the fit, can be used to estimate the expected number density of strong lenses as a function of the survey depth m in AB magnitude in the I-band:

$$N_{all} = 3.47 \times 10^{-34} m^{24.25}, \quad (1)$$

if all our candidates are included and

$$N_{a+b} = 5.18 \times 10^{-43} m^{30.4}, \quad (2)$$

if we keep only the class "a" and class "b" candidates, i.e., the most secure systems.

In Fig. 11, we also show the COSMOS number density of lenses, where only the 22 most secure systems are considered (see Table 3 in Faure et al. 2011). The lensing rate is slightly higher in COSMOS as discussed in Section 4, but still compatible with our empirical law. If we extrapolate our ACS lens counts to a $15\,000\,\text{deg}^2$ sky survey, we expect, following equation (1) (equation (2)) 34 030 (19 131), 128 892 (101 573), and 223 197 (202 170) lenses in optical surveys with depth of respectively $I = 24.8\,\text{mag}$, $26.2\,\text{mag}$, $26.8\,\text{mag}$.

The above counts are for the HST resolution in the I-band. Using these, we can attempt to estimate the number of strong lenses expected for a survey like Euclid (Laureijs et al. 2011). In order to do so, we have degraded our HST images of strong lenses to the Euclid resolution and sampling. This leads to unchanged lens counts compared with the HST, owing to the rather large angular size of all our systems. The limiting magnitude of

Euclid will be $m=24.5$ for the optical channel in the AB system. This $10\text{-}\sigma$ limit translates into a $3\text{-}\sigma$ limit of $m=25.8$. According to our equations (1) and (2), Euclid should therefore find 88 756 and 63 629 strong lenses, respectively.

It is not possible to provide precise lens counts per survey depth for our near-IR search, due to the many filters and exposure times applied.

6. Conclusion

We have conducted a visual search for galaxy-scale strong gravitational lenses in a total of 7 deg^2 of the sky, using archival HST images. The data comprise the whole ACS/WFC F814W imaging data available as of August 31st, 2011 (6.03 deg^2 , excluding the COSMOS field) as well as the WFC3 near-IR images (1.01 deg^2 in all filters) up to the same date.

We have found 49 new lens candidates: 40 in the ACS images and 9 in WFC3 images. Out of these, 16 are without any doubt genuine lenses, owing to their striking morphology. An additional 21 are excellent candidates and 12 have morphologies compatible with strong lensing but would need further investigation before being confirmed. If these candidates are indeed genuine lenses, they will contribute to broaden the variety of known lens morphologies and may prove useful to devise an train automated lens finders for ongoing and future all-sky surveys.

Our search for strong lenses is purely based on morphological criteria, with limited color information for 16 objects out of 49. It is not aimed at providing an homogeneous sample well suited for cosmology or galaxy evolution study, but rather to serve as a training set spanning a broad range of lensing configurations and useful for future automated searches. From our search, we conclude that, while the human-eye search may detect unusual lenses, such as faint arcs hidden in the glare of bright lenses or in complex/multiple lenses, it also has its specific biases as some genuine lenses will be discarded if only morphological criteria are used.

The large amount of data in the optical F814W band allows us to estimate the lensing rate as a function of depth, at the spatial resolution of the HST. We believe that these counts are lower estimates of the true lens counts owing to the high purity of the sample and probable incompleteness.

Scaling our lensing rate, we estimate that a $15\,000\text{ deg}^2$ optical survey such as Euclid will find at least 60 000 strong lenses down to $I=25.8\text{ mag}$ ($3\text{-}\sigma$), which is about 400 times the current number of known strong lenses in the same area of sky.

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References

- Alard, C. 2006, *astro-ph/0606757*
 Auger, M. W., Treu, T., Bolton, A. S., et al. 2010, *ApJ*, 724, 511
 Barnabè, M., Czoske, O., Koopmans, L. V. E., et al. 2009, *MNRAS*, 399, 21
 Bertin, E. 2011, in *Astronomical Society of the Pacific Conference Series*, Vol. 442, *Astronomical Data Analysis Software and Systems XX*, ed. I. N. Evans, A. Accomazzi, D. J. Mink, & A. H. Rots, 435
 Bolton, A. S., Burles, S., Koopmans, L. V. E., et al. 2008, *ApJ*, 682, 964
 Bolton, A. S., Burles, S., Koopmans, L. V. E., Treu, T., & Moustakas, L. A. 2006, *ApJ*, 638, 703
 Brownstein, J. R., Bolton, A. S., Schlegel, D. J., et al. 2012, *ApJ*, 744, 41
 Cabanac, R. A., Alard, C., Dantel-Fort, M., et al. 2007, *A&A*, 461, 813
 Capak, P., Aussel, H., Ajiki, M., et al. 2007, *ApJS*, 172, 99
 Dutton, A. A., Brewer, B. J., Marshall, P. J., et al. 2011, *MNRAS*, 417, 1621
 Faure, C., Anguita, T., Alloin, D., et al. 2011, *A&A*, 529, A72

Table 4. Image filters used to create the color images in Fig. 9. When only two filters are available, the mean of the two images was taken as the green channel.

Name	Red	Green	Blue
ACS J001423.02–302109.8	F814W	F606W	F435W
ACS J001426.26–302255.9	F814W	F606W	F435W
ACS J021634.62–051035.3	F814W	–	F606W
ACS J095139.44+684731.2	F814W	–	F606W
ACS J104701.80+171739.7	F814W	–	F435W
ACS J111052.23+284233.7	F814W	–	F555W
ACS J115135.05+004912.4	F814W	–	F435W
ACS J130042.73+280523.3	F814W	–	F475W
ACS J140237.11+542716.4	F814W	F555W	F435W
ACS J140339.94+541633.3	F814W	F555W	F435W
ACS J141649.81+522951.7	F814W	–	F606W
ACS J141657.72+433026.3	F814W	–	F606W
ACS J141710.17+433133.2	F814W	–	F606W
ACS J142028.48+525541.5	F814W	–	F606W
ACS J142158.70+531045.9	F814W	–	F606W
ACS J144000.07+313123.5	F814W	–	F606W
ACS J230325.68+085212.6	F814W	–	F435W

- Faure, C., Kneib, J.-P., Covone, G., et al. 2008, *ApJS*, 176, 19
 Faure, C., Kneib, J.-P., Hilbert, S., et al. 2009, *ApJ*, 695, 1233
 Gavazzi, R., Treu, T., Koopmans, L. V. E., et al. 2008, *ApJ*, 677, 1046
 Gavazzi, R., Treu, T., Rhodes, J. D., et al. 2007, *ApJ*, 667, 176
 Hu, W. 1999, *ApJ*, 522, L21
 Jackson, N. 2008, *MNRAS*, 389, 1311
 Koopmans, L. V. E., Treu, T., Bolton, A. S., Burles, S., & Moustakas, L. A. 2006, *ApJ*, 649, 599
 Lagattuta, D. J., Fassnacht, C. D., Auger, M. W., et al. 2010, *ApJ*, 716, 1579
 Laureijs, R., Amiaux, J., Arduini, S., et al. 2011, *ArXiv:1110.3193*
 Leauthaud, A., Massey, R., Kneib, J.-P., et al. 2007, *ApJS*, 172, 219
 Lintott, C. J., Schawinski, K., Slosar, A., et al. 2008, *MNRAS*, 389, 1179
 Marshall, P. J., Hogg, D. W., Moustakas, L. A., et al. 2009, *ApJ*, 694, 924
 More, A., Cabanac, R., More, S., et al. 2012, *ApJ*, 749, 38
 Moustakas, L. A., Marshall, P., Newman, J. A., et al. 2007, *ApJ*, 660, L31
 Peng, C. Y., Ho, L. C., Impey, C. D., & Rix, H.-W. 2010, *AJ*, 139, 2097
 Ratnatunga, K. U., Griffiths, R. E., & Ostrander, E. J. 1999, *AJ*, 117, 2010
 Scoville, N., Aussel, H., Brusa, M., et al. 2007, *ApJS*, 172, 1
 Seidel, G. & Bartelmann, M. 2007, *A&A*, 472, 341
 Suyu, S. H., Marshall, P. J., Auger, M. W., et al. 2010, *ApJ*, 711, 201
 Suyu, S. H., Treu, T., Blandford, R. D., et al. 2012, *ArXiv:1202.4459*
 Treu, T., Dutton, A. A., Auger, M. W., et al. 2011, *MNRAS*, 417, 1601

Table 2. List of lens candidates found from the HST/ACS data. Column 1: Identity number. Column 2: Lens candidate name. Column 3 and 4: Coordinates. Column 5: Radius of the arc in arc-second. Column 6: Total magnitude of the lensing galaxy in the F814W band, integrated in the 2-D light profile. The typical errors are 1 to 2%. Column 7: Effective radius in arcsec. The typical errors are 1 to 2%. Column 8: Lensing galaxy ellipticity, $\epsilon = (b/a)$. The typical errors are 1 to 2%. Column 9: Lensing galaxy position angle. Column 10: Comment, it describes the lensing candidate, see Section 3.3 for details. For candidate #33 (ACS J153234.81+324115.3) no satisfactory fit was obtained. The unrealistic effective radius is not reported nor plotted in the Fig. 10

ID	Name	RA h:m:s	DEC °:′:″	r_{arc} ″	I (lens) F814W	R_{eff} ″	ϵ	PA	Comment
01	ACS J001423.02–302109.8	00:14:23.02	–30:21:09.8	1.52	18.86	0.25	0.70	+39.1	A1b
02	ACS J001426.26–302255.9	00:14:26.26	–30:22:55.9	1.00	18.06	0.70	0.61	+30.2	A1a
03	ACS J005656.81–273841.0	00:56:56.81	–27:38:41.0	0.93	20.34	1.03	0.29	+15.3	A1b
04	ACS J010559.53–254438.0	01:05:59.53	–25:44:38.0	0.88	20.56	0.76	0.85	+41.5	A1b
05	ACS J011018.22+193819.5	01:10:18.22	+19:38:19.5	3.10	17.03	2.47	0.90	–32.7	A1a
06	ACS J021634.62–051035.3	02:16:34.62	–05:10:35.3	1.69	18.28	0.57	0.44	+06.1	A1b
07	ACS J084710.65+344826.4	08:47:10.65	+34:48:26.4	1.98	20.25	0.66	0.88	–74.1	A1a
					22.13	0.04	0.34	+23.3	
08	ACS J093323.88+441549.7	09:33:23.88	+44:15:49.7	1.32	19.71	0.26	0.93	–80.1	A1b
09	ACS J095139.44+684731.2	09:51:39.44	+68:47:31.2	0.77	19.78	0.50	0.71	+49.2	A1a
10	ACS J095718.69+685731.5	09:57:18.69	+68:57:31.5	0.82	18.62	1.29	0.91	+85.8	A1b
11	ACS J103751.40–124327.5	10:37:51.40	–12:43:27.5	1.48	19.25	2.04	0.54	+21.1	A1b
					19.99	0.68	0.54	–03.5	
12	ACS J104701.80+171739.7	10:47:01.80	+17:17:39.7	0.46	19.34	0.86	0.72	+64.5	P2b
13	ACS J111052.23+284233.7	11:10:52.23	+28:42:33.7	0.79	18.67	0.76	0.80	34.51	A2c
14	ACS J111127.06+285000.2	11:11:27.06	+28:50:00.2	0.39	21.02	1.50	0.69	+62.3	A1c
15	ACS J111715.58+174500.0	11:17:15.58	+17:45:00.0	0.95	19.68	0.49	0.82	+49.1	P2b
16	ACS J112310.02+141020.2	11:23:10.02	+14:10:20.2	1.01	20.50	0.18	0.50	–07.7	A1c
17	ACS J115135.05+004912.4	11:51:35.05	+00:49:12.4	1.87	19.10	0.16	0.77	+08.2	A1c
18	ACS J115138.59+004848.4	11:51:38.59	+00:48:48.4	1.96	19.12	1.24	0.41	–04.3	A1c
19	ACS J121637.27–120042.2	12:16:37.27	–12:00:42.2	1.46	21.27	0.16	0.77	–38.5	A1b
20	ACS J122332.64–123940.3	12:23:32.64	–12:39:40.3	0.36	19.68	0.19	0.54	+53.2	A1a
21	ACS J130042.73+280523.3	13:00:42.73	+28:05:23.3	1.08	17.56	1.46	0.62	–32.1	A1b
22	ACS J135401.12–123450.4	13:54:01.12	–12:34:50.4	2.95	19.32	1.35	0.83	–2.80	A1c
23	ACS J140237.11+542716.4	14:02:37.11	+54:27:16.4	1.85	17.99	1.38	0.71	–25.0	A1a
24	ACS J140339.94+541633.3	14:03:39.94	+54:16:33.3	0.90	18.66	3.44	0.34	+40.9	A1a
25	ACS J141649.81+522951.7	14:16:49.81	+52:29:51.7	0.34	20.82	0.94	0.96	+06.9	A1b
26	ACS J141657.72+433026.3	14:16:57.72	+43:30:26.3	0.78	20.82	0.16	0.79	–74.5	A1b
27	ACS J141710.17+433133.2	14:17:10.17	+43:31:33.2	2.14	18.16	4.94	0.39	+20.7	A1a
28	ACS J142028.48+525541.5	14:20:28.48	+52:55:41.5	0.61	19.67	0.56	0.91	–77.8	A1b
29	ACS J142158.70+531045.9	14:21:58.70	+53:10:45.9	0.82	22.38	0.40	0.59	+41.4	A1c
30	ACS J143542.20+342841.9	14:35:42.20	+34:28:41.9	0.96	19.96	1.77	0.43	–62.4	A1c
31	ACS J144000.07+313123.5	14:40:00.07	+31:31:23.5	0.60	22.08	0.12	0.61	+30.6	A1b
32	ACS J152702.08+355726.8	15:27:02.08	+35:57:26.8	1.73	19.59	1.16	0.68	+84.5	A1c
33	ACS J153234.81+324115.3	15:32:34.81	+32:41:15.3	1.21	18.54	16.67	0.38	+31.6	P4b
34	ACS J171750.68+593457.5	17:17:50.68	+59:34:57.5	1.79	17.92	0.68	0.77	+09.0	A1b
35	ACS J171817.43+593146.4	17:18:17.43	+59:31:46.4	2.35	15.21	2.72	0.79	+58.5	A1a
36	ACS J173923.28+690706.6	17:39:23.28	+69:07:06.6	1.23	20.94	0.14	0.38	+78.5	A1b
37	ACS J174035.58+690328.1	17:40:35.58	+69:03:28.1	1.12	19.08	0.63	0.31	+79.2	A1a
38	ACS J221501.12–135822.9	22:15:01.12	–13:58:22.9	0.82	19.10	0.78	0.22	–57.5	A1a
39	ACS J230325.68+085212.6	23:03:25.68	+08:52:12.6	0.72	17.62	1.08	0.35	–01.0	A1a
40	ACS J235130.60–261459.7	23:51:30.60	–26:14:59.7	3.32	16.26	2.49	0.74	–38.0	A1a

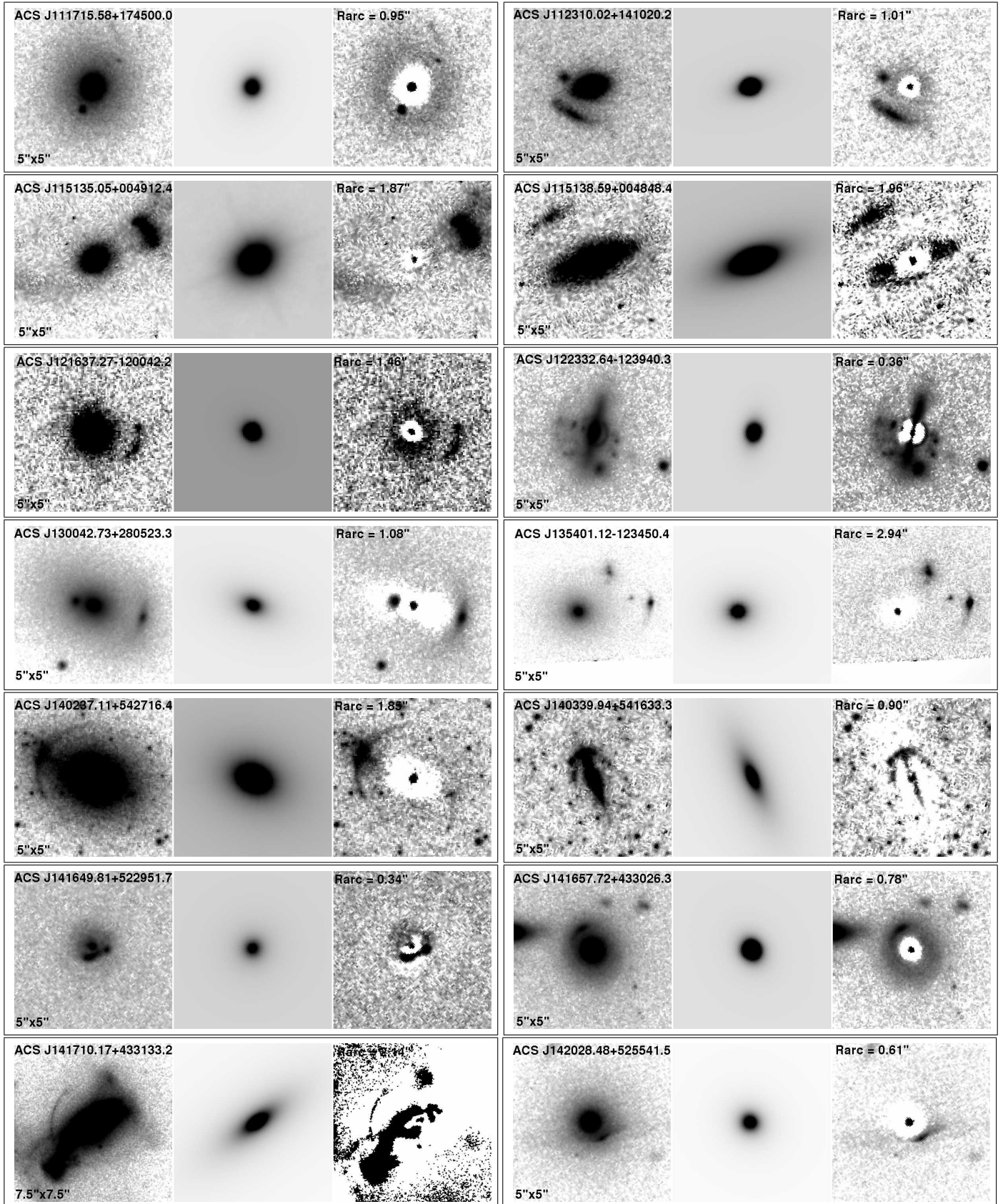


Figure 6. Continue Fig. 5.

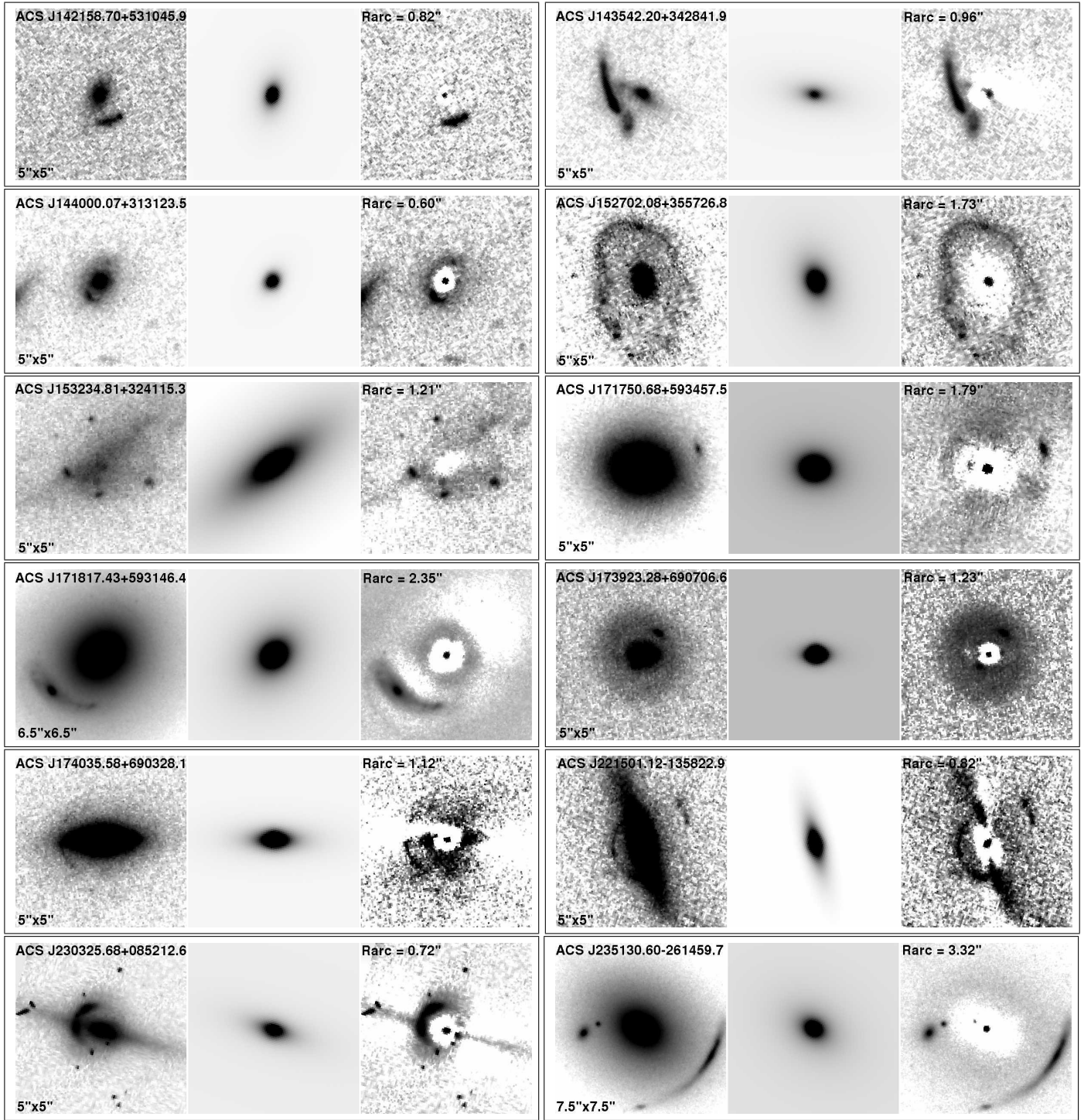


Figure 7. Continue Fig. 5.

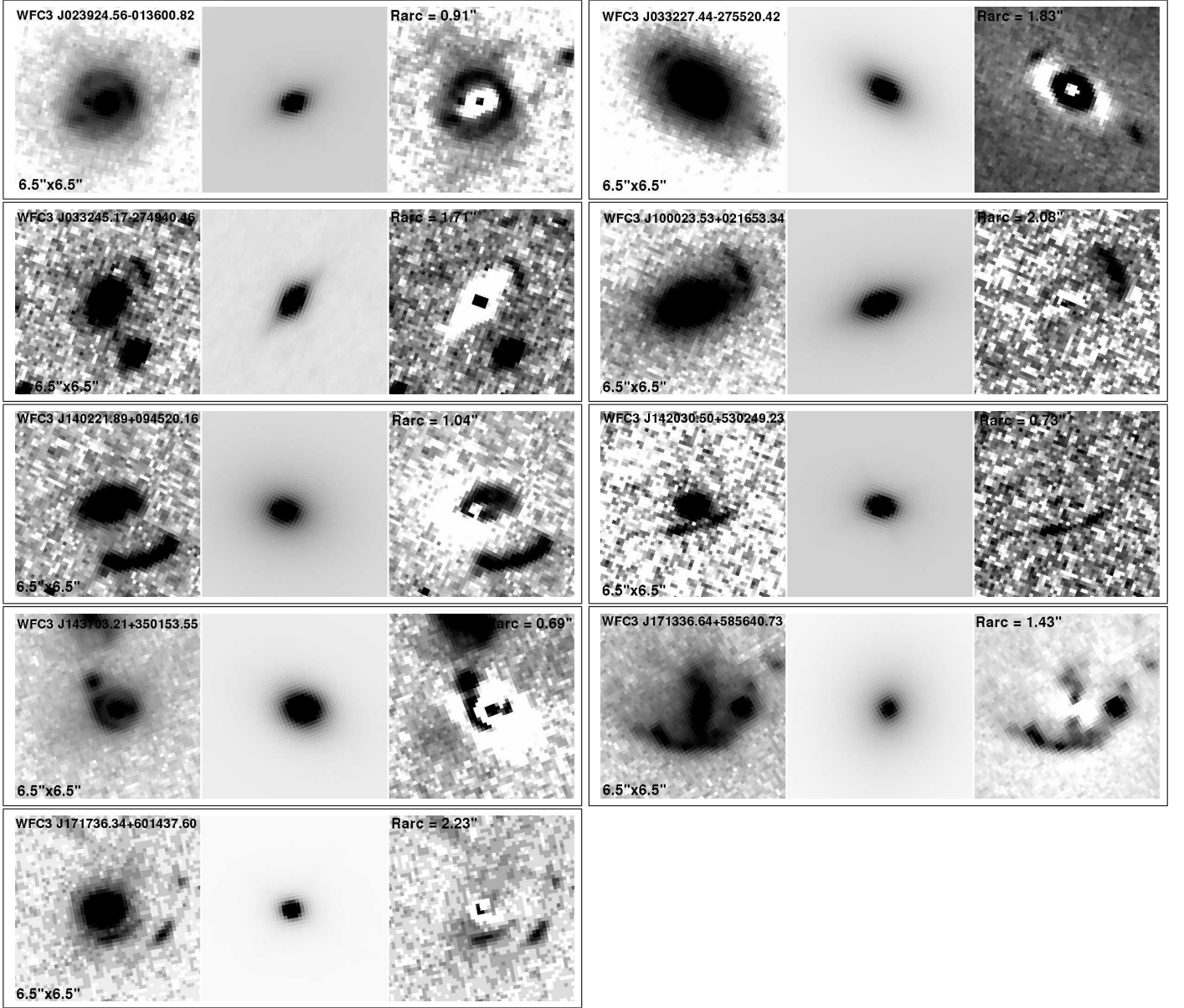


Figure 8. Lens candidates found by visual inspection of the WFC3 near-IR images. There are two lens candidates per line. For both are displayed in three panels : the WFC3 image, the 2-D light profile for the lens galaxy using GALFIT, and the image where the model is subtracted from the original data. Orientation of the images is north is to the top and East is to the left

Table 3. List of lens candidates found from HST/WFC3 data. The description of the columns is given in the caption of Table 2 except that the magnitudes are for the filter given in the "Filter" column.

ID	Name	RA h:m:s	DEC °:':"	r_{arc} "	R_{eff} "	ϵ	PA	Mag	Filter	Comment
1	WFC3 J023924.56-013600.82	02:39:24.56	-01:36:00.82	0.91	0.65	0.60	-56.5	20.50	F140W	R1b
2	WFC3 J033227.44-275520.42	03:32:27.44	-27:55:20.42	1.83	1.85	0.57	+75.9	18.35	F105W	A1a
3	WFC3 J033245.17-274940.46	03:32:45.17	-27:49:40.46	1.71	0.25	0.11	+67.9	20.48	F125W	A1a
4	WFC3 J100023.53+021653.34	10:00:23.53	+02:16:53.34	2.08	1.29	0.50	-49.8	19.33	F140W	A1b
5	WFC3 J140221.89+094520.16	14:02:21.89	+09:45:20.16	1.04	3.67	0.78	-73.0	20.13	F110W	A2c
6	WFC3 J142030.50+530249.23	14:20:30.50	+53:02:49.23	0.73	0.35	0.57	-81.4	22.84	F125W	A1c
7	WFC3 J143703.21+350153.55	14:37:03.21	+35:01:53.55	0.69	0.55	0.64	+40.7	19.87	F160W	R1a
8	WFC3 J171336.64+585640.73	17:13:36.64	+58:56:40.73	1.43	5.98	0.87	+45.0	19.07	F160W	A1c
9	WFC3 J171736.34+601437.60	17:17:36.34	+60:14:37.60	2.23	0.23	0.69	-12.6	20.69	F160W	A1b

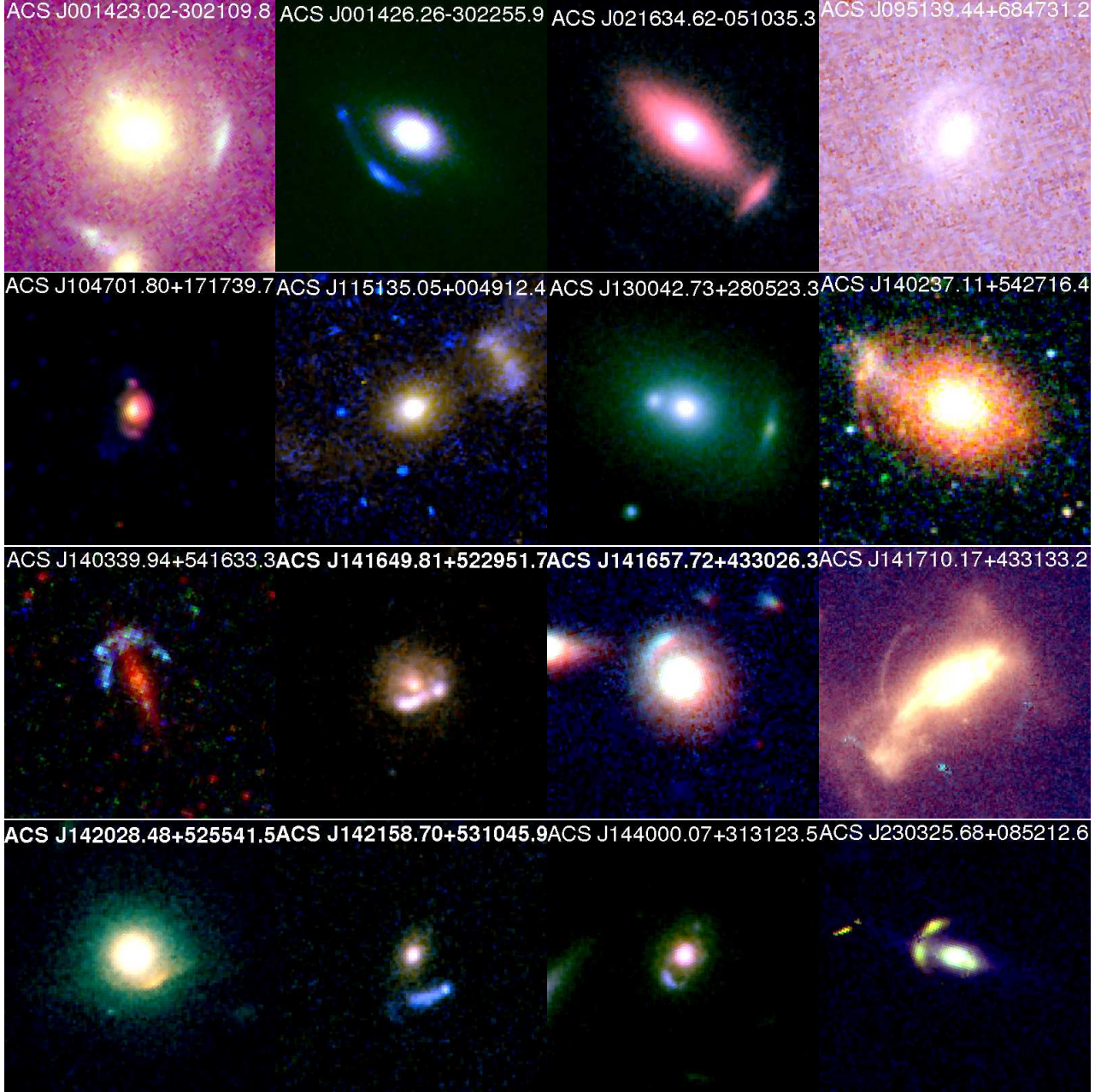


Figure 9. Color images of lens candidates. The individual filters used for creating these color images are listed in Table 4. Orientation of the images is north is to the top and East is to the left. And the image size similar to that of the black-and-white images in Fig. 5, 6 and 7.